

PHYSICS NEAR A BLACK-HOLE HORIZON

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Abstract

I discuss several general-relativistic effects that are likely to be of interest in the astrophysics of black holes and neutron stars

1 The horizon

The principal attribute of black holes, which makes them different from any other compact object, is the absence of a ‘hard’ surface. Finding the signature of this unique property in some observed systems would be the ultimate proof of black-hole existence. Until recently only the mass of a compact body in excess of the upper limit for neutron stars or, in the case of galactic nuclei, a mass concentration in excess of the upper limit for a sufficiently long-lived stellar cluster, could be used to decide that such a compact object belongs to the black-hole family. Some people prefer to call such objects black-hole ‘candidates’. We know now almost fifteen close binary systems, in which the compact object is believed to be a black hole (see e.g. Charles 2001) and a large number of galaxies (including our own) are believed to contain supermassive black holes in their centers (e.g. Magorrian et al. 1998). Are these objects true black holes? In the recent years Ramesh Narayan and his collaborators have established that X-ray luminosities of quiescent low-mass X-ray binary transient systems (also known under the name of ‘Soft X-ray Transients’ or ‘X-ray Novae’) containing compact objects selected as black holes because of their high masses, are much lower than the corresponding luminosities of system known to contain neutron stars and attributed this difference to the presence of an event horizon in the mass-selected objects (Narayan, Garcia, & McClintock 1997; Menou et al. 1999; Garcia et al. 2001, hereafter G2001). In other words, black hole ‘candidates’ would be true black holes. After some initial confusion about what the data are showing (see e.g. Chen et al. 1998) a suggestion by Lasota & Hameury (1998) that a luminosity vs period diagram is the most sensible way of

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deciding about differences between various systems has been adopted. Then, it appeared that although the luminosity difference between neutron stars and black-hole candidates is flagrant, neutron stars are nevertheless fainter than predicted by the model (Menou et al. 1999). The model in question assumes that the inner regions of the accretion flow in quiescent X-ray transients form an ADAF (see Lasota 1999 for a review). In such a radiatively inefficient flow most of the energy would be forever swallowed by a black hole but re-radiated from the surface if the accreting compact body is a neutron star, hence the difference in luminosities for the same accretion rate. It seems, however, that in neutron-star quiescent transient systems most of the accretion energy *is not* emitted from the surface of neutron stars (i.e. the accretion efficiency is much lower than the ‘standard’ value ≈ 0.1 ; see Menou et al. 1999 for details).

Abramowicz & Igumenshchev (2001) suggested that the observed differences between quiescent luminosities of accreting black holes and neutron stars can be explained by the presence of a CDAF (Convection Dominated Accretion Flow; see Narayan, Igumenshchev & Abramowicz 2000) in such systems. They found that for low viscosities accretion flows around compact bodies form ADAFs only in their innermost regions but are convectively dominated at radii $R \gtrsim 10^2 R_S$ (where $R_S = 2GM/c^2$ is the Schwarzschild radius). In such flows emission comes mostly from the convective region; the radiative efficiency is independent of accretion rate and equals $\varepsilon_{BH} = 10^{-3}$. Assuming that the efficiency of accretion onto a neutron star is $\varepsilon_{NS} \approx 0.1$ one obtains the observed ratio between black-hole and neutron-star luminosities. Unfortunately this cannot be the correct explanation of the luminosity difference because, as mentioned above, neutron stars in quiescent transient systems do not seem to accrete with a 0.1 efficiency (Menou et al. 1999).

Several suggestions have been put forward to explain this low efficiency. Winds from ADAFs, suggested by Blandford & Begelman (1999; Paczyński 1998 and Abramowicz, Lasota & Igumenshchev 2000 question the validity of the arguments presented in this article but their arguments do not preclude the existence of winds of e.g. magnetic origin) and modeled by Quataert & Narayan (1999) are not sufficient to explain neutron-star’s low accretion efficiency. Menou et al. (1999) proposed that the action of a magnetic propeller could be the answer, but a compelling signature of this effect has yet to be found. Finally, a simple and drastic suggestion was put forward by Brown, Bildsten, & Rutledge (1998): most (or all) of the quiescent X-ray luminosity is not due to accretion but results from cooling of the neutron-star crust heated by nuclear reactions.

The crust-cooling model, however, is apparently contradicted by the observed variations of the quiescent luminosity on a time-scale of years (Rutledge 2001a,b). Luminosity variations are observed also in quiescent black-hole systems (see e.g. G2001) which would suggest a common origin. Attempts to ascribe quiescent X-ray luminosity in these latter systems to black-hole’s companions (Bildsten & Rutledge 2000) are theoretically unsound (Lasota 2000) and have been refuted by observations (G2001). Lasota (2000) found that the correlation between quiescent luminosities and orbital periods of black-hole transients (three at that time) can be explained by a simple disc+ADAF model. However, *Chandra* observa-

tions (G2001) showed that things are more complicated, mainly because of the luminosity variations mentioned above.

Therefore, although observations seem to imply the presence of event horizons in bodies with masses higher than the neutron-star maximum mass, the uncertainties which still haunt accretion physics do not allow us to draw any definite conclusions in the matter.

2 The light

Light trajectories are strongly deflected close to the black hole surface. The best and the most beautiful images of a black hole surrounded by a luminous Keplerian disc were produced by Marck (1997). Marck (1996; see also Hameury, Marck & Pelat 1994) showed that using the Kerr - Schild coordinate system greatly simplifies the form of the geodesic equations in the Kerr metric and applied this form in numerical computations of black hole images. This method was also used to calculate spectra emitted near rotating black holes (Hameury et al. 1994). Jean-Alain Marck's work on images of a thin disc around a Kerr black hole was cut short by his untimely death in May 2000.

In the near future it might be possible to see images of black holes observed in X-rays by the *MicroArcsecond X-ray Imaging Mission* (MAXIM; <http://maxim.gsfc.nasa.gov>).

3 The disc

The best known general-relativistic effect in accretion disc structure is the existence of an Innermost Stable Circular Orbit (ISCO). It is the orbit where the Keplerian angular momentum has a minimum and marks the inner edge of a *Keplerian* accretion disc. It has been shown that it is also the place where, for geometrically thin discs, 'viscous' stresses approximately vanish ensuring flat angular momentum profile down all over to the surface of the black hole (e.g. Abramowicz & Kato 1989). The accretion efficiency is thus determined by the binding energy at this orbit. This conclusion has been recently challenged (see Hawley & Krolik 2000 and references therein) but, as recently recalled by Paczyński (2000), it is the angular momentum conservation that requires a 'no-torque inner boundary' for geometrically thin accretion discs around black-holes. Indeed, angular momentum conservation implies that at the sonic ring (which almost coincides with the inner disc's boundary):

$$\frac{v_r}{v_s} = 1 \approx \alpha \frac{H_{in}}{r_{in}} \frac{l_{in}}{l_{in} - l_0}; \quad r = r_{in}, \quad (3.1)$$

where v_r is the radial velocity, v_s is the sound velocity, $l(r)$ is the specific angular momentum at radius r (l_{in} is the specific angular momentum at the inner disc's edge r_{in} , and l_0 is an integration constant equal to the angular momentum at the inner flow boundary, i.e. at the black-hole surface).

In a thin disc $H_{in}/r_{in} \ll 1$, Eq. (3.1) implies that for small viscosities, i.e. for $\alpha \ll 1$, $(l_{in} - l_0)/l_{in} \ll 1$, i.e. the specific angular momentum at the sonic ring is almost equal to its value at the horizon.

In a stationary disc (accretion rate $\dot{M} = \text{const.}$) the torque g has to satisfy the equation of angular momentum conservation:

$$g = \dot{M}(l - l_0), \quad g_{in} = \dot{M}(l_{in} - l_0) \quad (3.2)$$

which shows that the ‘no-torque inner boundary condition’ is an excellent approximation for a thin, low viscosity disc. However, if the flow is thick, i.e. $H/r \sim 1$, and viscosity high ($\alpha \lesssim 1$), the angular momentum varies also between r_{in} and r_S .

These simple arguments have been confirmed by numerical calculations (Chen, Abramowicz & Lasota 1997; Armitage, Reynolds & Chiang 2001). This does not mean that no coupling is possible between a thin disc and a black hole – this only means that this coupling has to be global (‘non-viscous’) (see e.g. Blandford & Znajek 1977; King & Lasota 1977).

Non-keplerian ‘discs’ can extend down to the IBCO (‘B’ stands for *bound*; see Abramowicz & Lasota 1980, for the effect this has on the maximum angular momentum of an accreting black-hole). Still closer to the black-hole one finds in the IKCO (where ‘K’ stands for ‘Keplerian’), in other words the PCO (Photon Circular Orbit). The spatial 2D sphere at the locus of this orbit has strange properties discovered by Abramowicz & Lasota (see 1997 and references therein), which will be mentioned in Sect. 4

4 QPO’s, black holes and neutron stars

Timing observations of accreting neutron stars and black holes in Low Mass X-ray Binaries (LMXBs) reveal pairs of simultaneous high frequency ($\nu \gtrsim 50\text{Hz}$) Quasi-Periodic Oscillation (QPOs), which appear as peaks in the power spectrum (the Fourier transform of time variations) of the observed X-ray flux (see van der Klis 2000; Strohmayer 2001a,b).

Several ideas have been put forward to explain the double frequency peak phenomenon (see references in Strohmayer 2001a). Here I will mention only a recent suggestion by Kluźniak & Abramowicz (2001), who attribute the double peaks to a purely general-relativistic effect. As pointed out long time ago by Kato & Fukue (1980), the strong deviations from the $1/r$ law due to the presence of a scale (R_S) when the gravitational field of a spherical body is described by General Relativity, imply that the epicyclic frequency $\omega_r = (r^{-3}d^2l/dr)^{1/2}$ is different from the Keplerian frequency $\Omega_K = (GM/r^3)^{1/2}$ and has a maximum (see Fig. 1). For a Schwarzschild black hole this maximum is at $r_{\text{max}} = 4r_S$, ($\omega_{\text{max}} = \Omega(4r_S)/2$; at $r_{\text{ISCO}} = 3r_S$, $\omega_r = 0$). Therefore near the ISCO: $\Omega_K(r)/\omega_r(r) \rightarrow \infty$, as $r \rightarrow r_{\text{ISCO}}$ which, because the (radial) epicyclic motion is anharmonic, makes possible prominent 1:2, 1:3 resonances between $\Omega_K(r)$ and ω_r . Kluźniak & Abramowicz (2001) suggest that the high frequency QPOs are caused by such resonances. Strohmayer (2001a) observed a 450 Hz QPO simultaneous with the

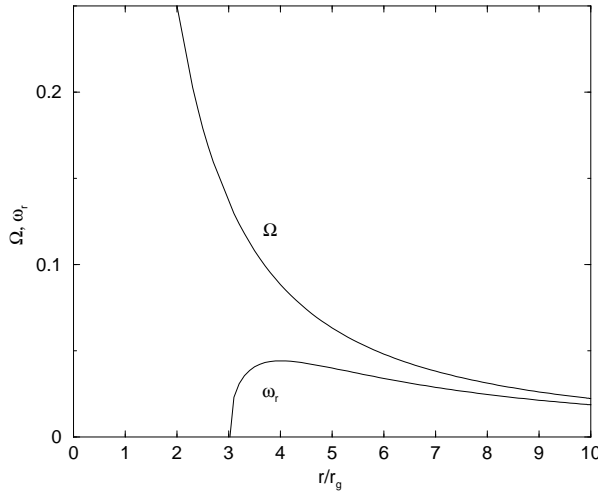


Fig. 1. Plots of the epicyclic frequency, ω_r , and the orbital frequency in circular orbits, Ω , both in units of c/r_g , are shown as a function of the circumferential radius in units of the gravitational radius $r_g = 2GM/c^2$ for the Schwarzschild metric (from Kluźniak & Abramowicz 2001).

previously known 300 Hz oscillation. The two frequencies are in a 3:2 ratio which could result from either the 1:2 or 1:3 resonances ($\Omega = 300$ Hz, $\Omega + \omega_r = 450$ Hz, or $\Omega = 450$ Hz, $\Omega - \omega_r = 300$ Hz) as predicted by the model (Abramowicz & Kluźniak 2001). However, explaining the pair of ~ 40 Hz and 67 Hz QPOs observed in GRS 1915+105 (Strohmayer 2001b), would probably require higher resonances.

Recently Heyl (2000) claimed that general-relativistic effects play an important role in the evolution of QPOs observed during type 1 X-ray bursts occurring at the surface of accreting neutron stars. In particular he found that the centrifugal force reversal at the locus of the circular photon orbit (Abramowicz & Prasanna (1990) is of importance. However, as shown by Abramowicz, Kluźniak & Lasota (2001; see also Cumming et al. 2001) this claim is erroneous.

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